

METHOD OF FORMING A NANO-SUPPORTED CATALYST ON A SUBSTRATE
FOR NANOTUBE GROWTH

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FIELD OF THE INVENTION

The present invention generally relates to a method of forming a nano-supported catalyst on a substrate, and more particularly to a method of forming a nano-supported catalyst on a substrate for nanotube growth.

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BACKGROUND OF THE INVENTION

A nanotube, and more specifically a carbon nanotube, is known to be useful for providing electron emission in a vacuum device, such as a field emission display. The use of a carbon nanotube as an electron emitter has reduced the cost of vacuum devices, including the cost of a field emission display. The reduction in cost of the field emission display has been obtained with the carbon nanotube replacing other electron emitters (e.g., a Spindt tip), which generally have higher fabrication costs as compared to a carbon nanotube based electron emitter.

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The manufacturing costs for vacuum devices (e.g., a field emission display) that use a carbon nanotube can be

further reduced if the carbon nanotube is grown on the field emission substrate from a catalytic surface using chemical vapor deposition or other film deposition techniques. Nanotube growth can be done as a last
5 deposition process preventing the degradation of the electron emitter properties by other device processing techniques or steps (e.g., wet processes). To further reduce costs for vacuum devices, it is also desirable to construct the field emission substrate from materials such
10 as borosilicate glass or sodalime glass. However, borosilicate glass and sodalime glass cannot generally tolerate temperatures above about sixty hundred and fifty degrees Celsius (650°C) and the tolerance of borosilicate glass and sodalime glass is further reduced if the
15 borosilicate glass or sodalime glass is subjected to temperatures above sixty hundred and fifty degrees Celsius (650°C) for an extended period of time or forces are applied to the borosilicate glass or sodalime glass at such temperatures.

20 In view of the foregoing, it is desirable to provide a nano-supported catalyst on a field emission substrate for carbon nanotube growth that allows such a carbon nanotube to be grown on the field emission substrate that has a deformation temperature below about six hundred and fifty

degrees Celsius (650°C). Furthermore, additional desirable features will become apparent to one skilled in the art from the drawings, foregoing background of the invention and following detailed description of a preferred exemplary
5 embodiment, and appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will hereinafter be described in
10 conjunction with the appended drawing figures, wherein like numerals denote like elements, and:

FIG. 1 is a flowchart of a first method for forming a nano-supported catalyst according to a preferred exemplary embodiment of the present invention;

15 FIG. 2 is an apparatus for forming a nano-supported catalyst according to a preferred exemplary embodiment of the present invention;

FIG. 3 is a flowchart of a second method of forming a nano-supported catalyst according to a preferred exemplary
20 embodiment of the present invention;

FIG. 4 is an illustration of a nano-supported catalyst prior to hot filament chemical vapor deposition that is formed with the method set forth in Example 1 of Appendix 1; and

FIG. 5 is an illustration of carbon nanotubes that have grown on the surface of the nano-supported catalyst shown in FIG. 4 after hot filament chemical vapor deposition.

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DETAILED DESCRIPTION OF PREFERRED EXEMPLARY EMBODIMENTS

The following detailed description of preferred embodiments is merely exemplary in nature and is not intended to limit the invention or the application and uses of the invention. Furthermore, there is no intention to be bound by any theory presented in the preceding background of the invention or this detailed description of preferred exemplary embodiments.

15 Referring to FIG. 1, a first method 100 is illustrated for forming a nano-supported catalyst on a substrate that can be used to grow nanotubes and preferably carbon nanotubes according to a preferred exemplary embodiment of the present invention. The method 100 begins with
20 providing a substrate having an electrode 102. The substrate is preferably borosilicate glass or sodalime glass, however any number of substrates can be used according to the present invention. For example, the

substrate can be other glasses, silicon, semiconductors, carbon, ceramics, metals and composite materials.

The electrode is preferably located on the substrate at the location in which the nano-supported catalyst is to be grown. The electrode can be any number of materials and can be configured on the substrate using any number of techniques. For example, the electrode can be a semiconductor or conductor, preferably a metal such as copper, that is formed on the substrate with any number of semiconductor or conductor deposition techniques (e.g., photolithographic patterning and deposition). Alternatively, the first method 100 and the second method 300 subsequently described in this detailed description of preferred exemplary embodiments with reference to FIG. 3 can begin with a substrate with a conductive surface layer having an unexposed portion that is covered by a photoresist and an exposed portion that is absent of the photoresist. The photoresist can be deposited and selectively exposed and removed using photolithographic patterning and etching techniques, with the exposed portion of the substrate configured as the electrode.

After the substrate having an electrode is provided according to the present invention, the substrate having the electrode is immersed into a solvent having a

first metal salt and a second metal salt 104. Any number of soluble metal salts can be used for the first metal salt and the second metal salt as long as the first metal salt and the second metal salt react at the electrode to form an insoluble metal, metal hydroxide, or metal oxide. For example, the first metal salt can be aluminum nitrate, magnesium nitrate, calcium nitrate or combination thereof, and the second metal salt can be a metal nitrate or sulfate containing iron, nickel, cobalt, ruthenium, rhodium, palladium, rhenium, osmium, iridium, platinum, or a combination thereof. The first and second metal salts are at least partially dissolved in any number of solvents, including, but not limited to, water, alcohol or a combination of water and alcohol (e.g., methanol, ethanol, and isopropyl alcohol). Additional compounds such as particles, surfactants, etc. can also be placed into the solvent.

The immersion of the substrate having the electrode into the solvent having the first metal salt and the second metal salt 104 can be accomplished with numerous immersion techniques, including, but not limited to, spin immersion, spray immersion, dip coating immersion, ink jet spraying followed by electrolysis, etc. Once the substrate having the electrode is immersed into the solvent having the first

metal salt and the second metal salt 104, the method 100 continues with the application of a bias voltage to the electrode such that a nano-supported catalyst is at least partially formed of the first metal and the second metal
5 salt 106.

Referring to FIG. 2, the application of the bias voltage to the electrode 202 is preferably applied with a biasing source 204 connected to the electrode 202 of the substrate 206 and a counter electrode 208 immersed in the
10 solvent 210 such that the nano-supported catalyst 212 is at least partially formed of the first metal salt (not shown) and the second metal salt (not shown) in the solvent 210. Alternatively, the counter electrode 208 can be located on the substrate 206 (not shown). For example, a negative
15 bias of less than about fifty (50) volts, preferably between about two (2) to five (2) volts, is applied for about sixty (60) seconds with the biasing source 204 between the electrode 202 on the substrate 206 of borosilicate glass and the counter electrode 208, which is
20 immersed in the solvent 210 of isopropyl alcohol with 1×10^{-2} M of salt aluminum nitrate ($\text{Al}(\text{NO}_3)_3$) (i.e., the first metal salt) and 1×10^{-3} M of ferric nitrate ($\text{Fe}(\text{NO}_3)_3$) (i.e., the second metal salt) with the electrode 202 on the substrate 206, such that a nano-supported catalyst 212 of

iron-aluminum oxide hydrate is formed on the electrode 202 of the substrate 206. As can be appreciated by one of ordinary skill in the art, the resulting iron-aluminum oxide hydrate is comprised of an insulating metal oxide support that is at least partially derived from the first metal salt and a conducting metal oxide that is at least partially derived from the second metal salt. During catalytic activity, the oxygen can be removed using conventional techniques (e.g., heating) from the conducting metal oxide that is at least partially derived from the second metal salt resulting in an active catalytic pure metal. However, as can also be appreciated by one of ordinary skill in the art, numerous variations of this example are available according to the present invention. (See Appendix 1 for additional examples that should not be construed as limiting embodiments of the present invention.)

Referring to FIG. 1, after the nano-supported catalyst is at least partially formed with the application of a bias voltage 106, the method 100 continues with the growing of nanotubes, preferably carbon nanotubes, on the nano-supported catalyst with a chemical reaction process such as catalytic decomposition, pyrolysis, or chemical vapor deposition (CVD), and preferably hot filament chemical

vapor deposition (HFCVD) 108. The techniques required for conducting these processes are known in the art. The nanotube growth temperature of the substrate during the chemical reaction process is a function of the substrate.

5 For example, the nanotube growth temperature of a substrate of borosilicate glass is preferably less than about six hundred and fifty degrees Celsius (650°C), more preferably less than about six hundred degrees Celsius (600°C) and most preferably less than about six hundred degrees Celsius
10 and greater than about five hundred degrees Celsius (500°C). As one skilled in the art can appreciate, the nanotube growth temperature of other suitable substrates may be higher than about six hundred and fifty degrees Celsius (650°C).

15 In a preferred embodiment, HFCVD is used to grow carbon nanotubes at the location of the nano-supported catalyst. HFCVD begins with introducing the substrate having the nano-supported catalyst into a CVD growth chamber. A refractory metal filament (e.g., tungsten,
20 platinum, rhenium, tantalum) is heated to a temperature above about nineteen hundred degrees Celsius (1900°C) in vacuum or as molecular hydrogen is flowed over the refractory metal filament. Carbon containing gases such as

methane, acetylene, and xylene can also be flowed over the filament to provide a carbon source for nanotube growth.

More specifically, the substrate with the nano-supported catalyst is placed into a thermally conducting
5 substrate holder (e.g., graphite) that is placed in a predefined location with respect to the hot filament (e.g., below the hot filament). The substrate holder can be a heater or it can be thermally connected to a heater. This configuration of the substrate with the nano-supported
10 catalyst and the hot filament allows the substrate's temperature (i.e., the nanotube growth temperature) to be independently controlled from the hot filament temperature. During the growth of at least one carbon nanotube and more preferably multiple carbon nanotubes on the nano-supported
15 catalyst of the substrate, the distance between the hot filament and the substrate is controlled to provide a temperature of the substrate (i.e., the nanotube growth temperature). For example, a distance of about one-half to about two centimeters (0.5 to 2 cm) between the hot
20 filament and the substrate is provided for a nanotube growth (or substrate) temperature ranging from about three hundred and fifty degrees Celsius (350°C) to about six hundred degrees Celsius (600°C).

Once the desired nanotube growth temperature is provided on the substrate, a carbon source is introduced into the CVD growth chamber. Any hydrocarbon or carbon-compound (e.g., methane, carbon monoxide, etc.) can be used
5 as the carbon source. For example, a gas mixture of hydrogen (H_2) and methane (CH_4) can be used as the hydrocarbon source, with a flow rate of one hundred (100) standard cubic centimeters per minute (sccm) for hydrogen and forty (40) sccm for methane. The methane is diluted by
10 the hydrogen (H_2) and thermally disassociated and activated with the hot filament. The ratio of the methane (CH_4) to hydrogen (H_2) is preferably maintained with the range of twenty percent (20%) to forty percent (40%) and the pressure of the CVD growth chamber is maintained at about
15 twenty (20) to fifty (50) torr. The simultaneous production of atomic hydrogen during hydrocarbon pyrolysis enhances the deposition of the carbon nanotubes and the growth of the carbon nanotubes is discontinued when the length of the carbon nanotubes is a desired length for a
20 particular application (e.g., the tips of the carbon nanotubes have grown to level of the gate aperture).

Referring to FIG. 3, a second method 300 is illustrated according to a preferred exemplary embodiment of the present invention for forming a nano-supported

catalyst on a substrate that has many desirable features, including nanotube and more preferably carbon nanotube growth. The second method 300 can use numerous materials, combinations * of materials, solvents, metal salts and
5 concentrations of metal salts in the solvent for the substrate, electrode, solvent(s), first and second metal salts and concentrations thereof, respectively, including the materials, combinations of materials, solvents, metal salts and metal salt concentrations in the solvent that
10 were previously discussed with reference to the first method 100 of FIG. 1.

The second method 300 begins as the first method begins with providing a substrate and an electrode 302. Thereafter, the substrate with the electrode is immersed
15 into a first solvent containing a first metal salt 304. While the substrate with the electrode is immersed in the first solvent containing the first metal salt 304, a bias voltage is applied from a counter electrode to the electrode such that a nano-supported catalyst is at least
20 partly formed with the first metal salt on the substrate at the electrode 306.

After the nano-supported catalyst is at least partly formed with the first metal salt on the substrate at the electrode 306, the substrate with the electrode is removed

from the solvent containing the first metal salt and immersed into a second solvent containing a second metal salt 308. A bias voltage is applied from a counter electrode to the electrode such that the nano-supported catalyst is partly formed with the second metal salt 310. The substrate with the electrode with the nano-supported catalyst is then dried and ready for introduction into a CVD growth chamber for growing at least one and more preferably multiple nanotubes on the nano-supported catalyst formed with the first metal salt and the second metal salt 312 as previously discussed with reference to the method 100 of FIG. 1.

Unlike other conventional catalysts formed by electro-deposition, which generally have active catalytic particles with at least one dimension (*i.e.*, diameter, width, length, or depth) that is greater than one micron (1 μm), the nano-supported catalyst formed according to the present invention has active catalytic particles with at least one dimension that is about one-tenth of a nanometer (0.1 nm) to about five hundred nanometers (500 nm), preferably less than fifty nanometers (50 nm) in size, more preferably less than about ten nanometers (10 nm), even more preferably less than about three nanometers (3 nm), and most preferably less than about one nanometer (1 nm), derived

from the second metal salt (e.g., iron, nickel, cobalt, ruthenium, rhodium, palladium, rhenium, osmium, iridium, or platinum, or a combination thereof) and supported by the metal oxide support derived from the first metal salt
5 (e.g., alumina, magnesium oxide, calcium oxide). Changing the composition ratio between the second metal salt and the remaining materials deposited to form the nano-supported catalyst structure can control the density of the active catalytic particles. The nano-support provided by the
10 metal oxide support maintains the nano-scale dimensions of the active catalytic particles through the useful temperature of the catalytic process including the chemical process described above for growing nanotubes (e.g., HFCVD) and prevent the active catalytic particles from coalescing
15 during such process. This nano-support renders the particle size independent of the nano-supported catalyst layer thickness and temperature cycle. Furthermore, the metal oxide support can prevent diffusion of poisons to the nano-supported catalyst and can enhance its chemical
20 reactivity. Due to its nano-supported structure, the nano-supported catalyst has a high surface area and a high surface area to volume ratio.

The nano-supported catalyst provided on the substrate with the first method 100 and the second method 300 of the

present invention allows nanotubes and more preferably carbon nanotubes to be selectively and sparsely grown on a micro-pattern (i.e., sub-pixel or quantum dots). The present invention provides single wall and multi-wall
5 nanotubes having a substantially uniform structure. The nanotubes formed according to the present invention preferably have a diameter less than about twenty nanometers (20 nm) and more preferably a diameter that is greater than about one nanometer (1 nm) and less than about
10 three nanometers (3 nm). In addition, the nanotubes formed according to the present invention preferably have an aspect ratio defined as height of the nanotube to the width of the nanotube that is about one hundred and forty (140) to about four thousand five hundred (4,500) and more
15 preferably from about one thousand (1,000) to three thousand five hundred (3,500) with a substantially perpendicular orientation with respect to the surface of the substrate. The preferred carbon nanotubes that are configured as electron emitters for a vacuum device such as
20 a field emission display provide a triode geometry from about one-tenth of a micron (0.10 μm) to about twenty-five microns (25 μm), a switching voltage that is less than about eighty (80) volts with a cathode current in the range of greater than greater than about one and a half milliamps

per square centimeter ($1.5\text{mA}/\text{cm}^2$) and a gate spacing less than about twenty-five microns ($25\text{ }\mu\text{m}$). Furthermore, the preferred nanotubes have significant dispersion in that they are spaced between about twenty nanometers (20 nm) to
5 two thousand nanometers ($2,000\text{ nm}$) apart and grown by the nano-supported catalyst that has active catalytic particles that are preferably less than about ten nanometers (10 nm) in size, more preferably less than about three nanometer (3 nm) in size, and most preferably about one nanometer (1 nm)
10 in size.

The nano-supported catalyst formed according to the present invention can also be used for numerous other applications such as a resistive material in a FED (e.g., ballast resistors) and a catalyst used in catalytic
15 converters, chemical synthesis, fuel cells, pollution control devices, or the production of scanning probe microscope tips, etc.

From the foregoing description, it should be appreciated that a nano-supported catalyst on a substrate
20 for nanotube growth and methods of forming a nano-supported catalyst on a substrate for nanotube growth are provided which present significant benefits that are described in the background of the invention and the detailed description of preferred exemplary embodiments, and also

would be apparent to one skilled in the art. Furthermore, while preferred exemplary embodiments have been presented in the foregoing description of preferred exemplary embodiments, it should be appreciated that a vast number of variations in the embodiments exist. Lastly, it should be appreciated that these embodiments are preferred exemplary embodiments only, and are not intended to limit the scope, applicability, or configuration of the invention in any way. Rather, the foregoing detailed description provides those skilled in the art with a convenient road map for implementing a preferred exemplary embodiment of the invention. It being understood that various changes may be made in the function and arrangement of elements described in the exemplary preferred embodiments without departing from the spirit and scope of the invention as set forth in the appended claims.

APPENDIX 1

EXAMPLE I

5 1. Immerse a borosilicate glass with a copper (Cu) metal pattern (i.e., substrate with an electrode) into a solution of 1×10^{-2} M $\text{Al}(\text{NO}_3)_3$ in isopropyl alcohol (IPA) and apply a negative twenty volt (-20V) bias to the copper metal pattern while keeping a counter electrode, which can
10 be constructed out of stainless steel, at ground for a duration of one (1) minute. The desired chemical reactions involved in this step are:

$\text{Al}(\text{NO}_3)_3 \rightarrow \text{Al}(\text{NO}_3)_2^+ + \text{NO}_3^-$ occurring in the solution;

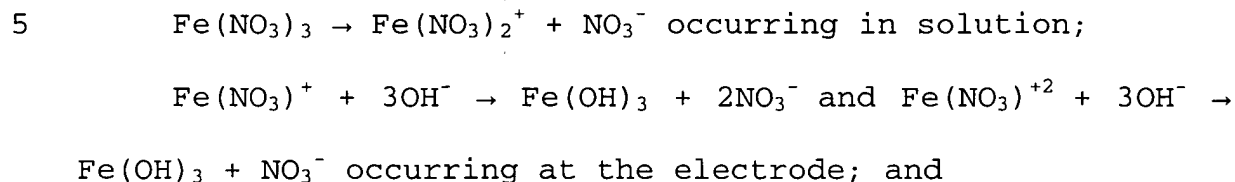
$\text{Al}(\text{NO}_3)_2^+ + 3\text{OH}^- \rightarrow \text{Al}(\text{OH})_3 + 2\text{NO}_3^-$ occurring at the
15 electrode; and

$\text{Al}(\text{OH})_3$ is the solid partial nano-supported catalyst that is forming at the electrode.

2. Dry the borosilicate glass with the copper metal pattern with the partially formed nano-supported catalyst
20 with a fifteen (15) minute bake at eighty degrees Celsius (80°C).

3. Immerse the borosilicate glass with the copper metal pattern with the partially formed nano-supported catalyst into a solution of 1×10^{-3} $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ M
25 (iron(III)nitrate hydrate) in IPA and apply a negative five

volt (-5V) bias to the copper metal pattern while keeping a counter electrode at ground for a duration of about one (1) minute. The desired chemical reactions involved in this step are:



$\text{Fe}(\text{OH})_3$ is the solid partial nano-supported catalyst that is forming at the electrode.

10 4. Dry the borosilicate glass with the copper metal pattern having the nano-supported catalyst formed of $\text{Al}_2\text{O}_3/\text{FeO}_x$ with a fifteen (15) minute bake at eighty degrees Celsius (80°C). (See FIG. 4 for an illustration of the nano-supported catalyst.)

15 5. Perform hot filament chemical vapor deposition (HFCVD) growth at five hundred and eighty degrees Celsius (580°C) with rhenium filament, and a gas mixture of methane (CH_4) and hydrogen (H_2) at a four to one ratio for thirty (30) minutes.

20 6. The resulting carbon nanotube film can be best described as a tangled carpet of carbon nanotubes with diameters on the order of about one nanometer (1 nm) to about three nanometers (3 nm) and an aspect ratio of

ranging from one thousand (1,000) to 2,000). (See FIG. 5 for an illustration of the nanotubes.)

EXAMPLE II

5 1. Immerse a borosilicate glass with a copper (Cu) metal pattern (substrate with an electrode) into a solution with $1 \times 10^{-2} \text{M}$ $\text{Mg}(\text{NO}_3)_2$ in isopropyl alcohol (IPA) and apply negative twenty volts (-20V) to the copper metal pattern while keeping a counter electrode, which can be constructed
10 out of stainless steel, at ground for a duration of one (1) minute. The desired chemical reactions involved in this step are:

$\text{Mg}(\text{NO}_3)_2 \rightarrow \text{Mg}(\text{NO}_3)^+ + \text{NO}_3^-$ occurring in the solution;

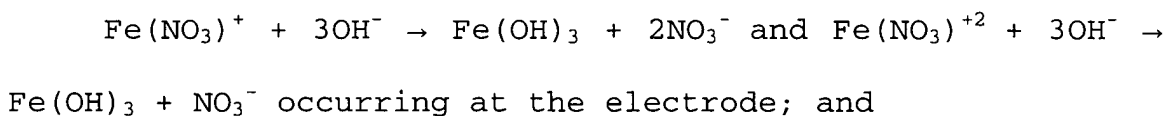
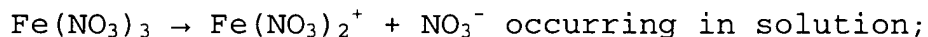
$\text{Mg}(\text{NO}_3)^+ + 2\text{OH}^- \rightarrow \text{Mg}(\text{OH})_2 + \text{NO}_3^-$ occurring at the
15 electrode; and

$\text{Mg}(\text{OH})_2$ is the solid partial nano-supported catalyst that is forming at the electrode.

2. Dry the borosilicate glass with the copper metal pattern having the partially formed nano-supported catalyst
20 with a fifteen (15) minute bake at eighty degrees Celsius (80°C).

3. Immerse the borosilicate glass with the copper metal pattern having the partially formed nano-supported catalyst into a solution of 1×10^{-3} $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ M

(iron(III)nitrate hydrate) in IPA and apply a negative five volt (-5V) bias to the copper metal pattern while keeping a counter electrode at ground for a duration of one (1) minute. The desired chemical reactions involved in this step are:



$\text{Fe}(\text{OH})_3$ is the solid partial nano-supported catalyst that is forming at the electrode.

4. Dry the borosilicate glass with the copper metal pattern with the formed nano-supported catalyst of $\text{Mg}_2\text{O}_2/\text{FeO}_x$ with a fifteen (15) minute bake at eighty degrees Celsius (80°C).

5. Perform hot filament chemical vapor deposition (HFCVD) growth at six hundred degrees Celsius (600°C) with rhenium filament, and a gas mixture of methane (CH_4) and hydrogen (H_2) at a four to one ratio for thirty (30) minutes.

EXAMPLE III

1. Immerse a borosilicate glass with a copper metal pattern (substrate with an electrode) into a solution with $1 \times 10^{-2}\text{M}$ $\text{Al}(\text{NO}_3)_3$ plus 1×10^{-3} $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ M in isopropyl

alcohol (IPA) and apply a negative ten volt (-10V) bias to the copper metal pattern while keeping a counter electrode, which can be constructed out of stainless steel, at ground for a duration of one (1) minute. The desired chemical
5 reactions involved in this step are:

$\text{Al}(\text{NO}_3)_3 \rightarrow \text{Al}(\text{NO}_3)^{2+} + \text{NO}_3^-$ and $\text{Fe}(\text{NO}_3)_3 \rightarrow \text{Fe}(\text{NO}_3)_2^+ + \text{NO}_3^-$
occurring in the solution;

$\text{Al}(\text{NO}_3)_2^+ + 3\text{OH}^- \rightarrow \text{Al}(\text{OH})_3 + 2\text{NO}_3^-$, $\text{Fe}(\text{NO}_3)^+ + 3\text{OH}^- \rightarrow$
 $\text{Fe}(\text{OH})_3 + 2\text{NO}_3^-$ and $\text{Fe}(\text{NO}_3)^{+2} + 3\text{OH}^- \rightarrow \text{Fe}(\text{OH})_3 + \text{NO}_3^-$ occurring
10 at the electrode; and $\text{Al}(\text{OH})_3$ and $\text{Fe}(\text{OH})_3$ are the solid
nano-supported catalyst that is forming at the electrode.

2. Dry the borosilicate glass with the copper metal pattern with the formed nano-supported catalyst of $\text{Al}_2\text{O}_3/\text{FeO}_x$ with a fifteen (15) minute bake at eighty degrees
15 Celsius (80°C).

3. Perform hot filament chemical vapor deposition (HFCVD) growth at six hundred degrees Celsius (600°C) with rhenium filament, and a gas mixture of methane (CH_4) and hydrogen (H_2) at a four to one ratio for thirty (30)
20 minutes.